

Ex-post Enforcement in Cooperative Spectrum Sharing: A case study of the 1695 - 1710 MHz band

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Abstract

Cooperative Spectrum sharing can be thought of as a reorganization of rights between stakeholders [2]. The principal stakeholders are the Primary User (PU), who holds the spectrum license, and the Secondary User(s) who uses the spectrum temporarily. Any rights management system requires a set of strategies and technologies to enforce the rights [3]; the timing of the enforcement action (ex-ante and ex-post) also plays a significant role [4]. The cooperative spectrum sharing approaches that have been proposed by the NTIA emphasize ex-ante actions, which are designed to prevent a PU's signal from harmful interference that could occur by the SU [1, 5]. A comprehensive enforcement framework would include protecting the rights of the SU in addition to having an ex post component that can efficiently and effectively adjudicate claims of interference. Determining the role of ex-post enforcement in a spectrum sharing scheme is of significant importance since cooperative spectrum sharing will without doubt result in interference events. To evaluate the role of the ex-post enforcement approach, a hypothetical scenario of using the recommended protection zones and the involved entities will be used to analyze the current enforcement timing measures and to evaluate the usage of ex-post-only enforcement measures. The hypothetical scenario concerns about the behaviors of the SUs, if SU-mobile devices transmitting near PU-base station or transmitting with high power signal within the protection zone. This behavior will cause harmful interference to the PU signal and data received by the PU will be lost. To guarantee SU behavior the suggested ex-ante and ex-post enforcement measures will be explained and analyzed. Then, ex-post-only enforcement measures will be applied to this scenario and analyzed. The purpose of analyzing the ex-post-only enforcement measures is to evaluate how these measures might work, and what the limits are on their effectiveness.

Introduction

Spectrum limitation and the inefficiency of spectrum usage has led to the new approach to communication policy of spectrum sharing. In the US, the National Telecommunication and Information Administration (NTIA) offered several bands for sharing between government agencies and commercial wireless service providers [1].

Spectrum sharing is a reorganization of rights between the spectrum sharing entities, and cooperation is one way of the coordinating spectrum sharing usage. The sharing entities are the Primary User (PU) who holds the spectrum license, and the Secondary User (s) who uses the spectrum temporarily. A set of strategies and technologies are required to enforce rights in any management system [3]. In addition, the timing of the enforcement action (ex-ante and ex-post) plays a significant role in such a management system [4]. The spectrum sharing approaches that have been proposed by the NTIA emphasize ex-ante

actions, which are designed to prevent a PU's signal from harmful interference that could occur by the SU [1, 5]. A comprehensive enforcement framework would include protecting the rights of the SU as well, in addition to having an ex post component that can efficiently and effectively adjudicate claims of interference.

In [6] the role of ex-post enforcement was evaluated by modeling how an ex-post only enforcement scheme might work. A model of a geographic region with geographically distributed SUs and a single PU was simulated to determine whether (and when) the ex-post approach is superior to an ex-ante approach. Aggregate signal power of the SUs were computed at the PU's antenna to calculate the interference level. We hypothesized an adjudication system would penalize the SU and that the penalty would be a fine equal to the value of the lost data plus the enforcement costs when the interference level reaches certain limit received at the PU's antenna in the model. This type of this penalty approach is categorized as remunerative penalty approach.

By following the approach that had been suggested in [6] the benefits for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas. The disadvantages that the PU might find are: (1) if the lost data cannot be recovered, (2) and a risk of Denial of Service (DoS) if the SUs keep transmitting near the PU-base station for a long time.

A purely remunerative penalty function may not be the best strategy; it might not be large enough to stop the SU from interfering with the PU. In this paper, we construct a broader framework for evaluating the role of the ex-post enforcement by modeling how an ex-post only enforcement scheme might work, and what the limits are on its effectiveness. This work will extend the work in [6] by exploring the other enforcement sanctions in the cooperative spectrum sharing regime when SUs conduct harmful interference. There are a number of aspects to consider, including what the sanctions are and how they should be applied to enforce the PU's rights.

This paper will study an ex-post-only enforcement to examine the role of ex-post enforcement in a cooperative spectrum sharing regime. A hypothetical scenario of using the recommended protection zones and the involved entities will be used to analyze the current enforcement timing measures and to evaluate the usage of ex-post-only enforcement measures. This hypothetical scenario about the behavior of the SUs is significant / of concern if SU-mobile devices transmit near PU-base station (earth station) or if they are transmitting high power signals within the protection zone. These behaviors will cause harmful interference to the PU signal and data received by the PU will be lost. The suggested ex-ante and ex-post enforcement measures will be explained and analyzed using this hypothetical scenario to see if SU guaranteed or not. Then, ex-post-only enforcement measures will be applied to this scenario and will be analyzed. The analysis of the ex-post-only enforcement measures is to evaluate how these measures might work, and what the limits are on their effectiveness.

To evaluate ex-post enforcement, we hypothesize an adjudication system by an enforcer that applies different enforcement sanctions on the Secondary User (SU). The enforcement sanctions will depend on the interference level and its duration caused by the SUs transmission. We will analyze two ex-post-only enforcement mechanisms. First, we will analyze the remunerative penalty approach. Then we will present a graduated response approach. In the graduated response approach, the interference levels will be divided into three different interference event levels received at the PU's antenna.

In the first interference level, the penalty would be a fine proportional to the lost data by the PU plus the expected increase in enforcement costs occasioned by it. In the second interference level, when the SU

does not optimize its transmission and decides to continue transmitting closer to the PU's antenna, more punitive penalties would be applied. The SU then optimizes their transmissions so that the net value of a sequence of transmissions is positive. In the third interference level, if the penalty value exceeds the maximum limit or the SU's interference duration exceeds a hypothesized maximum duration, other ex-post enforcement sanctions would be suggested like conditionally suspending SU license. We do not consider interference caused by "rogue" or "pirate" radios.

There are a number of phenomena that we study in this scenario. First, as the value for SU transmissions increase, SU may find it valuable to risk a higher interference penalty by transmitting closer to the PU's antenna. The levels of sanctions will encourage the SU to self-manage their transmission so that the value of a sequence of transmissions is positive and not to go through more sanctions forms that may lead them to lose the trust of the PU.

While the enforcer role will be discussed in future work, the above approach assumes that the adjudication that is applied by the enforcer is immediate and costless. To clarify the restrictions of adjudication costs, it was determined that the maximum hypothetical cost level of a region was equivalent to an exclusion zone in ex-ante enforcement. Having completed that, we articulate the effectiveness of an ex-post enforcement system and its technical requirements.

In the current static spectrum allocation, ex-ante-only measures make sense, but with a more dynamic spectrum sharing policy ex-post enforcement must play a role. This study will help researchers develop feasible approaches to adjudication and will help policymakers balance the use of ex-ante and ex-post enforcement techniques in spectrum sharing regimes.

This paper is organized as follows: section 2 will give historical background on the spectrum sharing and how it was introduced. Section 3 will introduce motivation and purpose from this work. Section 4 will define the general aspect of enforcement and its timing. Section 5 will define spectrum sharing methods. Section 6 will describe the case the paper is studying. Section 7 will analyze the recommended ex-ante and ex-post enforcement structures. Section 8 will give an alternative scenario of using ex-post-only enforcement. Finally, section 9 will offer conclusions to this work.

2. Background

The Federal Communication Commission (FCC) has begun gradually adapting its policies to include spectrum sharing. In 2002, the Spectrum Policy Task Force (SPTF) supported the idea of using the market method to utilize spectrum dynamically and efficiently [7]. In 2003, the FCC allowed the spectrum license holder to apply spectrum leasing options for wireless services [8]. In 2012, the President of the United States called for 500MHz of additional spectrum for mobile broadband [9]. The National Telecommunication and Information Administration (NTIA) offered several bands to support this effort through spectrum sharing. These spectrum bands will be shared between Federal/non-federal and commercial usage. The offered bands include [1]:

1. 1695-1710 MHz (the SU can use this band for uplink only)
2. 1755-1780 MHz (can be paired with 2155-2180MHz)
3. 3500- 3650 MHz (WiMax mobile stations)
4. 4200- 4220 MHz (cannot be available before 2016)
5. 4380- 4400 MHz (cannot be available before 2016)

3. Motivation and Purpose

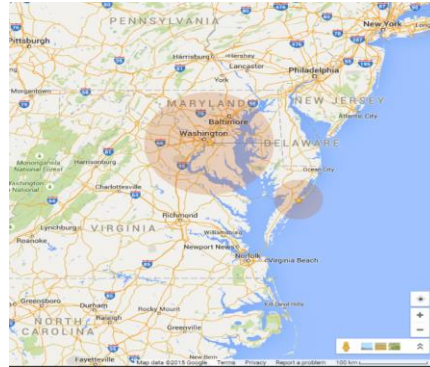
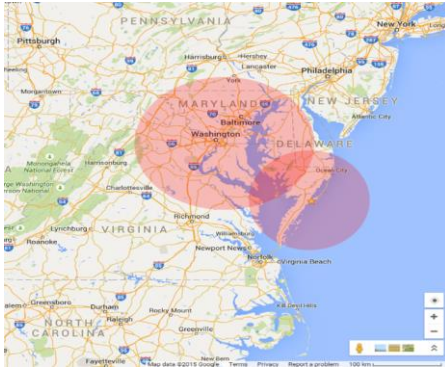
In 2010, the NTIA fast track report suggested that the 1695 - 1710 MHz band can be available for spectrum sharing with two main restrictions [10]. First, the Signal Interference to Noise Ratio (SINR) limitation of -10 dB that cannot be exceeded by the Secondary Users (SUs). Second, geographic limitations (called exclusion zones) in within which spectrum is not shared. The radii of these exclusion zones vary between 72-121 *km*, depending on the specific site. The lengths of the radii were given based on particular wireless systems used in their report. The length of the radii was established to prevent the Primary Users (PUs) from harmful interference. In 2013, CSMAC- WG1 recommended another geographical limitation to be used instead of exclusion zones which was called “protection zones” [11]. The SU could freely use the band outside the protection zone. SU need to coordinate with the PU (Federal organization) for using the band within the protection zone.

The exclusion zones will cover heavily populated areas that may reduce the incentives of the SUs to share. These two restrictions are examples of ex-ante enforcement and do not consider any ex-post measures that might be implemented. In contrast the protection zones, which are another example of ex-ante measures, will allow the use of spectrum after effective coordination between the Federal and the non-Federal organizations. The reason for using the protection zones is because the exclusion zones were impacting nearly thirteen percent of the United States (US) population. The radii of these protection zones vary between 16 - 98 *km*, depending on the specific site. The FCC adopted the protection zones in their Amendment rules with regard to commercial operation [12]. The protection zones reduced that impact on the US population to ten percent but the dedicated protection zones will still cover heavily populated areas that may reduce the incentive of the SUs to share.

In [6], an example was given to compare between using ex-post-only enforcement instead of ex-ante enforcement. It was found that the SU will find it beneficial to prefer ex-post-only enforcement because the radii of the penalty zone (no transmission zone) would be much smaller than the radii of the exclusion zone and therefore more users would benefit from spectrum sharing. The example was an approximation when implementing the ex-ante-only verses ex-post-only enforcements (see figure 1). Figure 1-a shows two of the exclusion zones denoted by the red circles (ex-ante enforcement only) which are Suitland, MD and Wallops Island, VA. These exclusion zones cover Washington, D.C. metropolitan area which is the seventh largest metropolitan area, and the Baltimore, MD metropolitan area. It can be seen that the PU will not share the band (1695 -1710MHz) within these two exclusion zones and the SUs can transmit only if they are outside these zones. Figure 1-b shows that when the adopted protection zone is used we can see that the protection zone radii for Suitland, MD is 98 *km* and it is impacting 3.1% of the US population. This protection zone also covers the Washington, DC metropolitan area and the Baltimore MD metropolitan area. By comparison, figure 1-c illustrates an ex-post-only enforcement scenario. Here, the SU transmissions are subject to a SINR limitation of -10dB and penalty if that limit is exceeded. The blue circles in Figure 1-c are much smaller than the exclusion zone or the protection zone. The SUs can transmit within these two zones too but they will be penalized. The main benefit is that spectrum can be shared in some major cities that are within the exclusion zones or protection zones.

a) Ex-ante only enforcement: two of the exclusion zones which are Suitland, MD and Wallops Island, VA

b) Ex-ante only enforcement: two of the protection zones which are Suitland, MD and Wallops Island, VA



C) Ex-post only enforcement: spectrum can be shared in all the area, and penalty zone is much smaller than exclusion zone

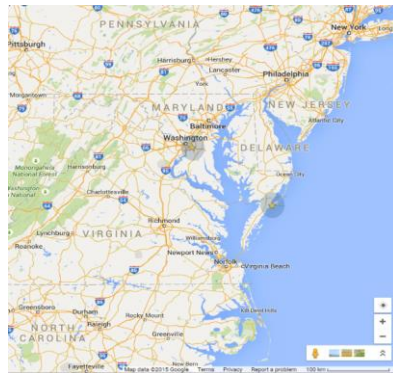


Figure 1 : Comparison between the radii of the exclusion zones and penalty zones.

In [6], the role of ex-post enforcement was evaluated by modeling how an ex-post-only enforcement scheme might work. A model of a geographic region with geographically distributed SUs and a single PU was simulated to determine whether (and when) the ex post approach is superior to an ex-ante approach. Aggregate signal power of the SUs were computed at the PU's antenna to calculate the interference level. We hypothesized an adjudication system that penalizes the SU for when the interference level reaches certain limit received at the PU's antenna. Remunerative penalty approach was used through imposing fines that was proportional to the lost value of the lost data by the PU plus the enforcement costs caused by it.

By following the approach that had been suggested in [6] the benefits for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas. On the other hand, the disadvantages that the PU may find are: (1) if the lost data cannot

be recovered, (2) and if the SUs keep transmitting near the PU for long time it will lead to denial of service (DOS) for the PU. But a purely remunerative penalty function may not be the best ex-post enforcement strategy, because it might not be large enough to stop the SU from interfering with the PU.

The purpose of this paper is to construct a broader framework for evaluating the role of the ex-post enforcement by modeling how an ex-post-only enforcement scheme might work, and what the limits are on its effectiveness. This work will extend the work in [6] by exploring the other enforcement sanctions in the cooperative spectrum sharing regime when SUs conduct harmful interference, continuously. There are number of aspects to consider, including what the sanctions are and how these sanctions might be applied to enforce the PU's rights.

4. Enforcement

In the past, the FCC assigned static spectrum bands to each user. Using this approach it was possible to prevent most of the interference between users. With the revolution in the telecommunications industry in the last two decades and the lack of spectrum bands, the federal government proposed certain bands to be shared [1, 7, 8] which leads to a rearrangement of rights. These new configurations of rights require enforcement systems if they are to be viable.

Any rights management system requires a set of strategies and technologies to enforce the rights [3] and the timing of the enforcement action (ex-ante and ex-post) plays a significant role [4]. The general characteristics of the enforcement of rights were explained elsewhere and, was applied to spectrum sharing in [5]. These characteristics are [3, 5]: 1) enforcement timing action (ex-ante or ex-post); 2) form of the sanctions; and 3) party (ies) carrying out the enforcement.

Shavell [4] argues that the timing of the enforcement action plays an important role in any enforcement regime. Enforcement actions can take place before (potential) interference events (ex-ante enforcement), or afterward (ex-post enforcement).

The spectrum sharing approaches that have been proposed by the NTIA emphasize ex-ante actions, which are designed to prevent a PU's signal from harmful interference that could occur by the SU [1, 5]. A comprehensive enforcement framework would include protecting the rights of the SU as well, in addition to having an ex post component that can efficiently and effectively adjudicate claims of interference.

As mentioned, practical enforcement schemes have ex-ante and ex-post enforcement that are linked together. Thus, the enforcement system will consist of: 1) ex-ante enforcement; 2) ex-post enforcement; 3) enforcer.

4.1 Ex-ante enforcement

Ex-ante enforcement procedures consist of prevention mechanisms that shape the activity before the harmful interference occurs. Examples of ex-ante enforcement are the exclusion zones, protection zones and the SINR limitations. Regulators prefer using an exclusion zone to prevent harmful interference because this is less complicated than other ex-ante enforcement mechanisms. A protection zone is another ex-ante enforcement mechanism but costs more because it requires coordination between the sharing entities when transmitting within the zone.

4.2 Ex-post enforcement

In telecommunications industry, the ex-post enforcement consists of corrective measures after a violation event has occurred. The corrective measures may include penalties (such as fines, product recall, or revocation of licenses) or modifications of rights between parties or other kinds of sanctions (e.g., power penalties, transmission moratoriums, etc.) such as in [20, 21].

The definition of penalty according to *The Law Dictionary*¹ is: “A punishment; a punishment imposed by statute as a consequence of the commission of a certain specified offense”. So, penalties are important in the telecommunications industry because (1) they encourage the violator not to impose harmful interference, (2) encourage the violator to look for alternatives to decrease the probability of a violation [13].

Generally, there are two approaches to determining penalties: remunerative and punitive. The punitive penalty means that if a breach event (such as harmful interference) occurs, the violator will pay much more than the real value of the breach (value of the lost data from harmful interference event). By contrast, a remunerative penalty seeks to compensate the injured for the value of the loss due the breach event.

Penalties could include fines only or fines and forfeiture. Imposing fines upon illegal offenders stems from the ancient Anglo-Saxon tradition of extracting payment from families and sometimes whole communities for the commission of criminal acts [15]. The term “fine” is defined as a financial penalty enforced in illegal matters [14]. In the United States (US), fines are usually designated for particular offenses; because of existing statutes they are restricted to minimum and maximum amounts. As an example, a fine for speeding in an automobile must fall between \$30 and \$300.

The Communications Act of 1934² regulates harmful interference in the telecommunications industry and this Act rules have been used to apply to the present day practice of spectrum sharing. The Act imposes a base value for fines depending on the violation; it also sets maximum limits depending on the nature of the offense according to section five of the Act. Section five dictates the penalties when conducting harmful interference by any individuals [15]. The penalty levels vary depending on the degree of the violation or level of harm. If it causes harm to another entity the general penalty is a fine of no more than \$10,000 (section 501). In the case of violating the rules or the regulations of the Communications Act of 1934, the violator will be punished with a fine of no more than \$500 for each and every day of the breach (section 502).

In the case of repeating harmful interference, the penalty is upgraded to a forfeiture penalty based on the Communication Act of 1934. The FCC uses Forfeiture Proceedings³ to issue additional penalties according to the Communications Act of 1934. For the purpose of this paper, we are going to explore different measures such as punitive penalty and conditionally suspending spectrum license.

¹ What is Penalty?: <http://thelawdictionary.org/penalty/>, (accessed on April 29, 2015)

² Communications Act of 1934 (last visited 8/2/15): <https://transition.fcc.gov/Reports/1934new.pdf>

³ Forfeiture Proceedings guidelines (last visited 8/2/15): http://www.ecfr.gov/cgi-bin/text-idx?SID=6c4588fbf26be630b7d3ce1862fbee3e&mc=true&node=se47.1.1_180&rgn=div8

4.3 Enforcer

The role of the enforcer would be to detect, adjudicate, and control parties' behaviors. The enforcer must be trusted by all the entities of the system and must have authority to resolve enforcement violation events [16]. The parties could elect the enforcer to resolve both the acceptability of a hypothetical violation event and its costs [16].

In the US, telecommunications agencies can be divided into two types: federal agencies and non-federal commercial agencies. Each type of agency has a different enforcer (entity) to govern spectrum usage. NTIA has authority over federal spectrum users but has no authority over non-federal users. Conversely, the FCC governs non-federal spectrum use but has no authority over federal spectrum users [15]. As a result, a legal framework for implementing an enforcement function must be developed.

5. Spectrum Sharing

Spectrum can be shared in three dimensions which are spatial dimension, frequency, and time. Spectrum can also be shared in any combination of those dimensions. Static spectrum allocation means a spectrum user will have exclusive rights to the spectrum when the spectrum is not being shared in at least one of those dimensions.

The current wireless networks are defined by a static allocation policy that has been regulated by the government since the 1920s [12]. That policy led to lack of spectrum in particular spectrum bands and the spectrum usage was concentrated on a certain portion of the assigned spectrum. This resulted in to a large amount of the assigned spectrum being unutilized. The limited available spectrum and the insufficiency in the spectrum usage required a new communications standard policy that could offer new ways of exploiting the available spectrum. Spectrum sharing was proposed to solve these issues.

Spectrum sharing can be viewed as a readjustment of rights among stakeholders [1]. The FCC started to move toward spectrum sharing and changing its strategies toward spectrum allocation gradually. In 2002, the Spectrum Policy Task Force (SPTF) supported the idea of using the market method to utilize spectrum dynamically and efficiently. In 2003, the FCC allowed the spectrum license holder to apply spectrum leasing options for wireless services. In 2012 [10] the President of the United States called for 500MHz of spectrum for mobile broadband. To ease spectrum sharing, (NTIA) offered several bands, previously mentioned in the background section of this paper [1].

5.1 Spectrum Sharing Methods

There are a variety of methods to manage spectrum sharing between entities. The sharing entities are the license holder (or the spectrum incumbent) who is referred to as the primary user (PU) and the secondary user (SU) who is using the spectrum temporarily. Weiss and Lehr [12] presented a taxonomy of sharing depends on the presence of explicit coordination of usage (figure 2). The Cooperative sharing, which is the primary focus of this paper, depends on the coordination between users. The sharing coordination could be between PU and SU users or between SU users themselves. Non-Cooperative sharing, applies when there is no coordination between users. Cooperative and Non-Cooperative parties have two types of sharing: Primary and Secondary. Primary sharing means all users have equal rights whether they are sharing the spectrum (i.e. using WiFi) or using it for the secondary spectrum market. Secondary Sharing

means there is no coordination between PU and SU but there could be coordination between SUs via medium access control (MAC) protocol.

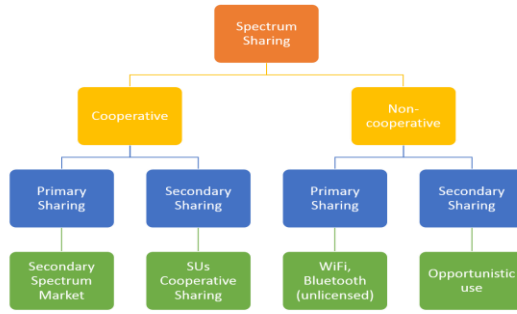


Figure 2: ways of Spectrum Sharing

6. Case Description

We will focus on the 1695 - 1710 MHz band in this paper because enables a clear exposition of enforcement concepts; other bands will be studied in future. The PU of 1695 - 1710 MHz band is the National Oceanographic and Atmospheric Administration (NOAA) using this band for the downlink from the Federal Meteorological Satellite (MetSat). The PU is using this band for the downlink from satellite to base stations to receive weather data. PU's base stations are fixed, not mobile. The Secondary Users (SU) for this band will be non-federal commercial organizations. The SU is assumed to be an LTE operator who will be using this band for uplink from the handsets to the base station. The band will be shared between PU and SUs.

A Commerce Spectrum Management Advisory Committee counsels NTIA on a wide range of spectrum policy matters. CSMAC-Working Group 1 (CSMAC-WG1) was charged with developing recommendations for the use of the 1695 - 1710 MHz band. These recommendations will be toward commercial services and protecting federal meteorological earth stations from harmful interference. CSMAC-enforcement subcommittee concerns with the enforcement rules of spectrum sharing [15].

In 2013, CSMAC recommended that the protection zones be used instead of the exclusion zones with the same SINR limitation that had been suggested in the NTIA fast track report in 2010. Then the FCC adopted the protection zones in its Amendment rules with regard to commercial operation in 2014 [12]. The SU could freely use the band outside the protection zone. The SU need to coordinate with the PU (federal organization) for using the band within the protection zone. And this coordination will need an enforcer to govern spectrum sharing enforcement rights.

The behavior of the SUs is significant because of the danger it poses for harmful interference. If SU-mobile devices transmit close to a PU-earth station or transmit a high power signal within the protection zone, harmful interference to the PU signal may occurs, resulting in the possible loss of PU data. The impact of losing such data might be very high in case of weather emergency.

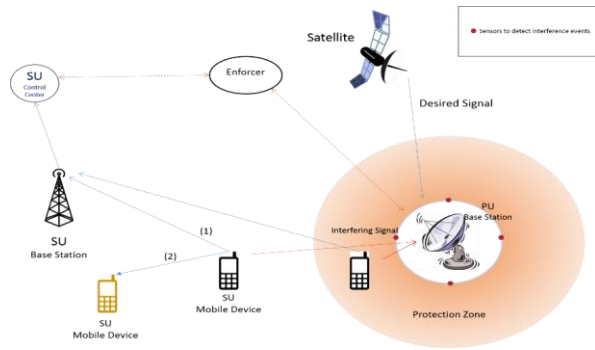


Figure 3: Spectrum sharing entities and sharing scenarios using protection zone

Figure 3 shows our hypothetical scenario using the protection zones and the involved entities. This hypothetical scenario will be used throughout the paper to analyze the current enforcement timing measures and to evaluate the usage of ex-post-only enforcement measures. This hypothetical scenario demonstrates the potential concerns/consequences of an SU-mobile device transmitting data or a high power signal near the PU earth station within the protection zone. To avoid this outcome, the suggested ex-ante and ex-post enforcement measures will be explained and analyzed. Then, ex-post-only enforcement measures will be applied to this scenario and analyzed to evaluate how these measures might work, and the limitations on their effectiveness.

Figure 3 shows three entities will be involved in spectrum sharing: the PU, a single SU mobile operator, and an enforcer. The band will be shared between PU and SUs. PU will be an earth base station and will be using this band for a downlink signal from the satellite. The Secondary User (SU) is a non-federal commercial agency that is assumed to be an LTE operator. In figure 3, we can see that an SU-mobile device outside the protection zone can use the band as an uplink to an SU-base station as link (1), or it can use the band to communicate with other SU's mobile devices as a link (2) to cooperate with other SUs. Within the protection zone we assume that only Cooperative Primary Spectrum sharing between PU and single SU will be used. The enforcer role is to coordinate between the PU and SUs to guarantee their behaviors. The enforcer will need to detect the interference events that affect the PU's received signal and are caused by the SU's uplink signal. To do this a sensing system will need to be built around the PU earth station.

6.1 Ex-ante enforcement in Cooperative Spectrum Sharing

The CSMAC-enforcement subcommittee recommended that the NTIA along with the FCC identify the ex-ante measures of the operational and technical guidelines governing the spectrum sharing of Federal Government ("Federal Government" does not need to be capitalized) bands. These guidelines include interference mitigation and enforcement procedures to provide ample precision for PUs and prospective SUs [15]. So, the ex-ante enforcement that will be applied to the spectrum sharing are 1) protection zones; 2) SINR limitation of -10 dB to establish the interference threshold for the receivers of the PU's receiver (metrological-satellite earth station's receiver).

6.2 Ex-post enforcement in Cooperative Spectrum Sharing

The ex-post enforcement consists of corrective measures after harmful interference has occurred. The corrective measures may include penalties (such as fines, product recall, or revocation of spectrum sharing licenses) or modifications to spectrum sharing rights between PUs and SUs.

Ex-post enforcement measures in spectrum sharing cases are different because the spectrum is going to be shared between Federal/non-federal and commercial usage. And each type of these agencies has a different entity to govern the spectrum usage. Those entities each have different ex-post measures. The entity that governs the Federal spectrum users is the NTIA but has no authority over non-federal users. Conversely, the FCC governs non-federal users but has no authority over federal spectrum users [15]. That is why we see differences in ex-post enforcement measures between NTIA and the FCC.

The FCC has a variety of ex-post enforcement measures such as Notice of Apparent Liability and penalties. As previously mentioned, penalties may play an important role in spectrum sharing because (1) they deter the violator from conducting harmful interference; (2) encourage the violator to look for alternatives thereby decreasing the probability of repeated harmful interference [13]. The FCC penalties such as fines, forfeitures, cease and desist orders, equipment seizures and in the most extreme cases criminal penalties. In addition, the FCC governmental procedure consists of technical rights, as well as trials, in advance penalties are confirmed [15]. NTIA ex-post enforcement measures are different than the FCC because it is dealing with federal agencies. NTIA has the authority to modify and revoke Federal licenses.

The CSMAC-enforcement subcommittee report recognized the differences and difficulty of relying on one entity (NTIA or FCC) to govern if a harmful interference event occurred between PU and SUs [15]. It recommended that NTIA and the FCC enter into a new central Memorandum of Understanding (MOU) to govern spectrum sharing rights between federal and non-federal users. By central MOU, federal and non-federal entities would rely on both the FCC and NTIA to take necessary actions in the event there is a breach of a sharing agreement. The central MOU would combine both agencies' ex-post enforcement measures and apply them when SU is transmitting within the protection zones. By using the central MOU 1) SUs will depend on NTIA authority to take action against the PU in the event there is a breach of spectrum sharing arrangement; 2) and PU will rely on the FCC authority to enforce spectrum sharing rights over SUs. CSMAC-enforcement subcommittee report also recommended that both PU and SUs enter into specific MOU to cover all specific interference concerns regarding spectrum sharing rights.

6.3 Enforcer

The enforcer would govern PU and SU behaviors to 1) guarantee spectrum sharing rights are enforced; 2) and **guarantee that PU will not receive any harmful interference signals from the SU**. The enforcer would need to detect the interference events that affect the PU's received signal and are caused by the SU's uplink signal. A sensing system would need to be built around the PU (which is an Earth Base Station in this model). The sensor network would then detect the aggregate signal energy attributable to the SU. The sensor antennas would have a range equal to the protection zone ranges (16- 98 km) depending on the specific site. If the signal energy is below noise level, it would not be detectable. If the signal energy reaches the noise level, interference would be detected and the enforcer will apply the ex-post enforcement measures recommended by the central MOU, such as penalizing the SU. Details about the enforcer role and sensing its mechanisms, are matters for future work and will not be discussed here.

Commented [MW1]: An enforcer can't actually make this guarantee!

6.4 Violating Spectrum Sharing Rights

In case one of the sharing entities violates the rule of spectrum sharing, the enforcer would use both central MOU and specific MOU that integrate NTIA and FCC ex-post enforcement measures. In the event the PU violates spectrum sharing rights, the enforcer could apply the NTIA corrective measures, such as modification, and revoke federal licenses of the PU. And if the SU violates any spectrum sharing rights by conducting harmful interference, the Communications Act of 1934⁴ would be used to regulate this event by using a section 5 Forfeiture penalty SU would be classified as a common carrier because it is an LTE operator (non-federal commercial agency). The maximum forfeiture amount per harmful interference or per day for a continuing interference is \$160,000. If the harmful interference continued by SU involving single act or failure to act, the statute limits of forfeiture penalty for SU is going to be \$1,575,000.

In addition to these fines, central MOU would use and integrate Forfeiture Proceedings guidelines⁵ used by the FCC to issue penalties in addition to any other penalty provided by the Communications Act of 1934. The guidelines would be used to issue no forfeiture at all, a higher or lower forfeiture than provided in the Communications Act of 1934, or to apply alternative or additional sanctions as permitted by the statute.

Based on Buckley⁶ and Acumen⁷ cases, we hypothesize that the forfeiture penalty consists of three factors which are 1) the base amount forfeiture expense for transmitting close to PU-base station and exceeding the power limits; 2) base forfeiture expense for interference; 3) and upward or downward adjustment factor. The base amount forfeiture expense for transmitting near a PU base station and exceeding the power limits is \$4,000. The base forfeiture expense amount for interference is \$7,000. The downward or upward adjustment factor depends on the violation act and it relies on section 503 (b)(2)(E) of the Communications Act of 1934 to consider the nature, circumstances, extent and gravity of the violations and with respect to the violator, the degree of liability, any history of prior violations, capability to pay, and such other measures as justice requires. Therefore, the adjustment factors regarding the severity of the violation that may increase or decrease the forfeiture such as substantial harm, repeated or continuous violation, or substantial or economic gain derived from the violation, and the minor nature of the violation.

7. Analysis of the recommended Ex-ante and Ex-post Enforcements

7.1 Ex-ante enforcement

The two ex-ante measures that have been recommended are 1) protection zones, 2) and the Signal Interference to Noise Ratio (SINR) limitation of -10 dB that cannot be exceeded by SUs. The main reason for using the protection zones instead of exclusion zones was the population impact in the US. The previous recommendation of using exclusion zones would affect thirteen percent of the US population but using the protection zones reduced that impact to ten percent of the US population. When using the

⁴ Communications Act of 1934 (last visited 8/2/15): <https://transition.fcc.gov/Reports/1934new.pdf>

⁵ Forfeiture Proceedings guidelines (last visited 8/2/15): http://www.ecfr.gov/cgi-bin/text-idx?SID=6c4588fbf26be630b7d3ce1862fbee3e&mc=true&node=se47.1.1_180&rgn=div8

⁶ FCC Forfeiture Order for Mr. Drew Buckley, Bay Shore, NY (last visited 7/21/2015): <https://transition.fcc.gov/eb/Orders/2014/DA-14-880A1.html>

⁷ FCC Forfeiture Order for Acumen Communication (Acumen), Los Angeles, California (last visited 8/2/15): <https://www.fcc.gov/document/17k-nal-acumen-unauthorized-operation-and-harmful-interference>

protection zone, the SU could freely use the band outside the protection zone. SU need to coordinate with the PU for using the band within the protection zone. The protection zones allow the use of spectrum within the zone after effective coordination between the PU and SUs. The radii of these protection zones vary between 16-98 km, depending on the specific site.

However, the impact on the US population was not solved in the use of the protection zones. And still the dedicated protection zones will cover heavily populated areas that may reduce the incentives of the SUs to share. As an example, one of the protection zones is Suitland, MD and the recommended radii is 98 km. It covers the Washington, DC metropolitan area which is the seventh largest metropolitan area, and Baltimore, MD metropolitan area. This protection zone only impacts 3.1% of the US population, but is significant because it will affect the methods of spectrum sharing within protection zones. The only method that is allowed to be used within the protection zones is the Cooperative Primary Spectrum Sharing.

7.2 Ex-post Enforcement in Spectrum Sharing

Ex-post enforcement is needed in spectrum sharing to control the behavior of the sharing entities. So, if the SU violates the spectrum sharing agreement by conducting harmful interference, the PU will rely on the FCC's ex-post enforcement measures to stop the SU from continuing or repeating this violation. The FCC has a variety of ex-post enforcement measures such as Notice of Apparent Liability and penalties. FCC relay on the Communications Act of 1934 to regulate harmful interference event by using a Forfeiture Proceedings guidelines⁸. The Forfeiture Proceedings guidelines are used to issue no forfeiture at all, a higher or lower forfeiture than provided in the Communications Act of 1934, or to apply alternative or additional sanctions as permitted by the statute depending on other factors.

$$\text{Forfeiture} = Op + I \pm Adj - - - - (1)$$

Equation (1) is the forfeiture penalty which consists of three factors: 1) Op is the base amount forfeiture expense for transmitting near to PU base station and exceeding the power limits; 2) I is base forfeiture expense for interference; 3) and $\pm Adj$ is upward or downward adjustment factor. The base amount forfeiture expense for transmitting near PU base station and exceeding the power limits is \$4,000. The base forfeiture expense amount for interference is \$7,000. The downward or upward adjustment factor depends on the violation act and it rely on section 503 (b)(2)(E) of the Communications Act of 1934⁹ to consider the nature, circumstances, extent and gravity of the violations and with respect to the violator, the degree of liability, any history of prior violations, capability to pay, and such other measures as justice require. Therefore, the adjustment factors regarding the severity of the violation that may increase or decrease the forfeiture such as substantial harm, repeated or continuous violation, or substantial or economic gain derived from the violation, and the minor nature of the violation. Based on the Communications Act of 1934, the forfeiture penalty can be upgraded until it reaches the maximum limit. The maximum forfeiture amount per harmful interference or per day for a continuing interference is \$160,000. If the harmful interference continued by SU involving single act or failure to act, the statute limits of forfeiture penalty for SU is going to be \$1,575,000.

⁸ Forfeiture Proceedings guidelines (last visited 8/2/15): http://www.ecfr.gov/cgi-bin/text-idx?SID=6c4588fbf26be630b7d3ce1862fbee3e&mc=true&node=se47.1.1_180&rgn=div8

⁹ Communications Act of 1934 (last visited 8/2/15): <https://transition.fcc.gov/Reports/1934new.pdf>

The issue with these ex-post enforcement measures that had been used by the NTIA and FCC are based on the Communications Act of 1934, these ex-post enforcement measures are suitable for static spectrum allocation policy but may not be applicable for spectrum sharing policy and might reduce the incentives for the SU to share the spectrum because of the following:

- 1- Regulation
 - a. They are based on the Communications Act of 1934 Section 302(1) (transfer the authority to the FCC to govern the likely interference of devices but it did give the authority for FCC or NTIA to give this authority to a trusted third party).
 - b. They are more generic.
 - c. They are more punitive than corrective measures for individual cases.
 - d. There is no alternative to the Forfeiture Proceeding guidelines when harmful interference event occurs that the enforcer can follow.
- 2- Technically: The band is dedicated for the uplink communication from SU-mobile devices to SU-base station. SU is a mobile operator and cannot control the mobility of the SU-mobile devices. If an SU-mobile device moved close to the PU's base station and tried to communicate with SU-base station, it might affect receipt of the satellite signal for PU and lead to harmful interference. The consequences for that would be implemented by the enforcer, who would follow the FCC Forfeiture guidelines by forfeiting the mobile devices and applying the forfeiture penalty to the SU.
 - a. If this happened once, the enforcer might go with no forfeiture at all or have the authority to upgrade the forfeiture penalty until it reaches the maximum amount of \$160,000 but that is not explained well in the CSMAC-enforcement subcommittee recommendation.
 - b. If it occurred a second time in the same day, the enforcer would have the authority to upgrade the forfeiture penalty to the maximum amount of \$160,000.
 - c. If the violation occurred for the second time in another day, the enforcer would have the authority to upgrade the forfeiture penalty up to the maximum amount of \$1,575,000.
 - d. Sometimes the SU-mobile devices transmit a signal with high power to communicate with the SU-base station until it receives a signal from the SU-base station to lower its power. If the SU-mobile device is transmitting near PU's base station that would lead to harmful interference and the enforcer might follow the procedure that had been mentioned in the previous point.

The CSMAC-enforcement subcommittee recommended that PU and SU enter into specific MOU or individual agreement to cover all specific interference enforcement issues [15]. The specific MOU would framework enforcement rights and proper penalties of the sharing parties. This recommendation will not be an ideal solution because it will be under the umbrella of the Communications Act of 1934 and the Forfeiture Proceedings guidelines. In addition, the Forfeiture Proceeding guidelines did not take into consideration the time period of conducting the harmful interference. The time period of the interference is needed to impose the proper penalty to cover the value of lost data. The Forfeiture Proceeding did not put into consideration the number of the interferer because it was based on the static spectrum policy and the interference cases were rare.

Alternatively, CSMAC-enforcement subcommittee could be more specific and recommend that PU and SU enter into specific MOU to cover other ex-post enforcement (interference remedies) that are related to spectrum sharing. Ex-post enforcement that are not included in the Communication Act of 1934 such as other types of penalties (fines) against the interferer such as remunerative or punitive penalties depending on the level and time of the interference. The following sections will evaluate the scenarios of using those two approaches in the spectrum sharing regime to find which is better approach that could be used.

8. Alternative Scenarios

8.1 Ex-post enforcement only- Remunerative Penalty Approach

In [6] the role of ex-post-only enforcement using a remunerative penalty approach shows the regulator how an ex-post-only enforcement scheme might work. A model of a geographic region with geographically distributed SUs and a single PU was simulated to determine whether (and when) the ex-post approach is superior to an ex-ante approach. Aggregate signal power of the SUs were computed at the PU's antenna to calculate the interference level. It hypothesized an adjudication system that penalizes the SU for when the interference level reaches certain limit received at the PU's antenna. A remunerative penalty approach was used which means a fine was imposed on the SU that was proportional to the lost value of the lost data by the PU plus the enforcement costs caused by it. The remunerative penalty was imposed for each SU-mobile device's conduct harmful interference to the PU's received signal and considered the time period for the interference.

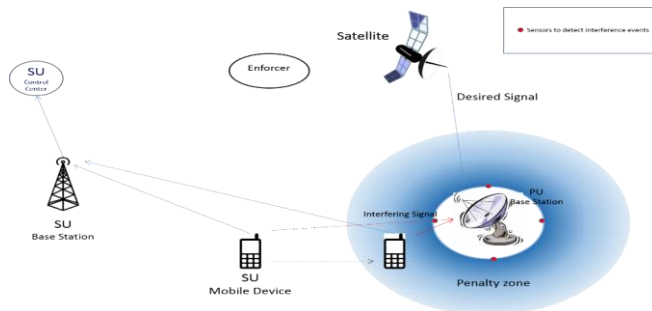


Figure 4: Spectrum sharing entities and sharing scenarios using ex-post enforcement- remunerative approach

Figure 4 shows the hypothetical scenario used in [6] of using ex-post-only enforcement. Three entities involved in spectrum sharing which were PU, single SU mobile operator, and an enforcer. The band would be shared between PU and SUs. PU would be an earth base station and it would be using this band for downlink signal from the satellite. The Secondary Users (SU) is a non-federal commercial agencies which is assumed to be LTE operator. SU used this band for uplink from the handsets to the SU's base station. The enforcer role was to govern the spectrum sharing rules between the PU and SUs to guarantee their behaviors. The enforcer would need to build sensors around the PU's base station to detect the interference events that affect the PU's received signal and are caused by the SU's uplink signals. The sensor's antenna would have a range to detect the interference events with probability of detection, called a penalty zone. The PU would share the spectrum within the suggested exclusion zones if (1) the SUs agreed on the spectrum sharing rights that included the SINR limits of -10 dB and (2) if any interference event occurred the SUs would be penalized by the enforcer. The SU would not be penalized as long as its interfering signal does not exceed the interference limits (-10 dB).

The penalty function in [6] was built on Polinsky and Shavell [18] argument that ex-post enforcement costs has two types which are unchangeable enforcement costs and changeable enforcement costs. Unchangeable enforcement costs are the costs that do not depend on the number of interferer which is the value of the transmission loss due to interference. Changeable enforcement costs depends on the

number of SUs that go beyond the interference limits, such as costs of penalizing the interferer and collecting penalties. Equation (2) represents the remunerative penalty function that is imposed by the enforcer to each SU-mobile device exceeds the SINR limits. The enforcer charges a Penalty to the SU that recovers PU's (1) transmission loss due to interference (\$ I) for the time t and (2) the changeable enforcement costs (\$ C) which represents the costs of imposing and collecting the penalties (3) all multiplied by a probability of detection (α) because the number of interference events depend on this probability. Undetected interference should not increase the penalty. The PU cannot know for certain what α is, so it is a private estimate. It could adjust the Penalty (\$ I) by α , but not the changeable cost (\$ C). The penalty function will be as follows:

$$\text{Remunerative Penalty} = \alpha(I \times t + C) \text{ --- (2)}$$

So, the SU can decide to transmit or not based on:

- Its estimation of received aggregate signal power at PU or SINR limits of $\geq -10\text{dB}$ by benefiting from the use of propagation model.
- Its estimates of probability of detection (α) (presumably SU knows the values of changeable and unchangeable enforcement costs. If the value of transmission is greater than or equal the Remunerative Penalty, the SU will transmit.
- Otherwise, if the value of transmission is less than the Remunerative Penalty, the SU will not transmit.

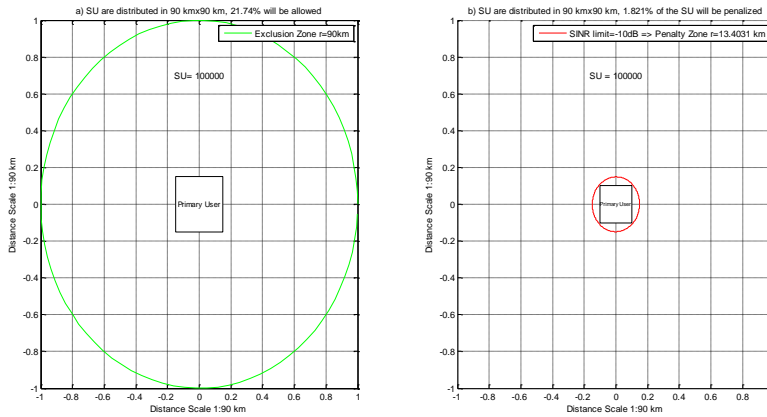


Figure 5: comparison between suggested exclusion zone and Penalty zone

By following the approach in [6], a simple model of geographic region with geographically distributed SUs and single PU was built. Figure 5 shows a comparison between the suggested exclusion zone in the NTIA fast track report [1] with a length of 90km and a penalty zone. It was assumed that 100,000 SUs were uniformly distributed in the area of 90km \times 90km. The interference limit of -10dB was used to build the penalty zone with a range of 13.4km (see Appendix A for more detail about the propagation model and other assumptions). Figure 5-b shows that the penalty zone range was smaller than the exclusion zone

and even smaller than the recommended protection zone since the smallest suggested protection zone is 16km.

The benefits of using ex-post-only with remunerative approach that had been suggested in [6] for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas, (3) the cost of building the sensors around the PU's base station to detect harmful interference is less than the one for protection zones because it would have a smaller range. The disadvantages that the PU may find are: (1) if the lost data cannot be recovered; (2) this approach would not stop the SU from conducting harmful interference to PU because as the value for SU transmissions increase, SU may find it valuable to risk a higher interference penalty by transmitting closer to the PU's antenna; (3) if the SUs keep transmitting near the PU for an extended period of time it would lead to denial of service (DOS) for the PU; (4) and imposing the penalties depend on the probability of detection. So if the probability of detection is 50%, the SU will be detected once every two times of conducting harmful interference and that means PU will get paid once instead of two events of losing data.

8.2 Ex-post enforcement only- Punitive Penalty Approach

To overcome these disadvantages the enforcer could use punitive penalties. The same hypothetical scenario will be used on figure 4 of using ex-post-only enforcement but with punitive penalty approach. The punitive penalty will be imposed for each SU-mobile device's conduct harmful interference to the PU's received signal and considered the time period for the interference. The main reason from using punitive penalty is to deter the SU from conducting harmful interference on the PU receiving signals which will lead to loss of data. So when constructing the punitive penalty function, the enforcer and the sharing entities have to put in consideration of under deterrence or over deterrence.

As mentioned, a punitive penalty approach means the value of the fine is much higher than the value of PU's lost data. Polinsky and ~~shavell~~ Shavell [19] argued that ~~Punitive-punitive~~ damages ordinarily should be awarded if, and only if, a person who cause harm has a chance of escaping responsibility for the harm ~~causescaused~~. In the spectrum sharing regime, the enforcer will detect the interference events by using a sensor ~~antennas~~. These sensors ~~antenna~~ will have a ~~sufficient~~ range to detect the interference events with probability of detection (α). ~~So, the condition of using punitive penalty becomes valid in our hypothetical scenario.~~ Polinsky and Shavell [19] argued that if the SU has a chance of not being detected, the suitable level of total loss to impose on ~~them~~ (if SU-mobile device is detected) is the value of the lost data multiplied by the equivalent of the probability of detection. Thus if the value of the lost data is \$1,000 and the probability of detection is 50% which means that there is a 50% chance that interferer SU-mobile device will found responsible, the penalty fine should be ~~multiplied by the damage/0.5, or twice the damage, or 2.~~ ~~So the total punitive penalty value should be \$2,000 which is the value of the lost data \$1,000 plus the punitive costs of \$1,000 in this example. Because the SU will pay this value every second time SU mobile devices generate harmful interference.~~ Similarly, if the probability of detection is 25%, punitive penalty should be \$4,000 (the value of the lost data \$1,000 multiplied by 4). They defined the ideal level of punitive costs should be equal to the value of the lost data multiplied by a punitive factor. The punitive factor can be represented as the ratio ~~between-of~~ the probability of detection ~~over-and~~ the probability of escaping. So, the punitive penalty function will consist of two values: ~~which are~~ the value of the lost data and the value of the punitive costs.

$$\text{Punitive Penalty} = (\$I \times t + \$C) + adj \text{ --- (3)}$$

Equation (3) represents the punitive penalty function that is imposed by the enforcer to each SU-mobile device exceeds the SINR limits. The punitive penalty function consists of two fields added together. The first field, is representing the value of the unchangeable enforcement cost ($\$I$) multiplied by the time (t) and changeable enforcement costs ($\$C$). The second field, represent the adjustment factor (adj). The function of the adjustment factor could be linearly, or exponentially calculated.

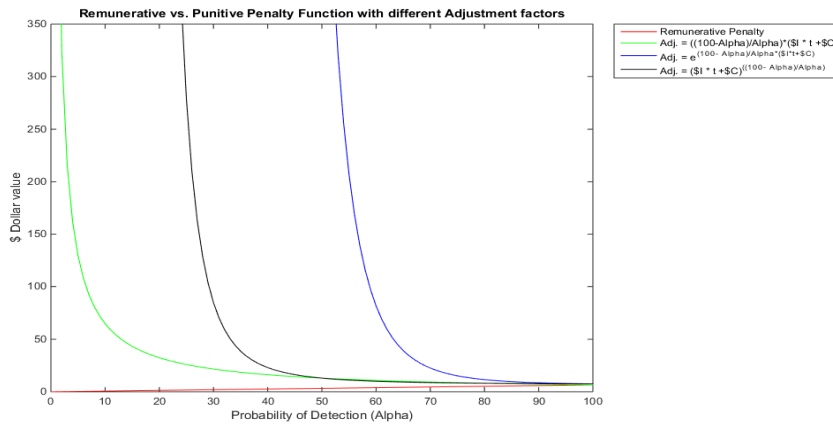


Figure 6: Remunerative Penalty vs. Punitive Penalties with different adjustment factors

The punitive penalty function should guarantee that the SU will pay the value of the lost-data lost that had been caused due to from the harmful interference, thus take suitable provisions for not conducting harmful interference. Figure 6 shows a comparison between the remunerative penalty and punitive penalty with different ways of calculating the adjustment factors. The result is calculated when there is one SU-mobile device is exceeding the SINR limit and causing loss of the receiving the PU's signal. The value of the lost data and the changeable enforcement costs were chosen to be equal¹⁰. We can see that the SU penalty will be much higher than the value of the lost data when as the probability of detection is getting smaller decreases. We can see that when the probability of detection is less than 25% with the punitive penalty function, it will may be preferable to use a linear adjustment factor that is equal to punitive factor multiplied by the value of the lost data because the other two approaches would be considered as to be over-over-deterrence. Also, if the probability of detection is less than 55%, it will be preferable not to use the natural exponential function for the same reason. The issue of using ex-post enforcement with punitive penalty approach only, it would not stop the SU from repeat conducting

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¹⁰ To estimate the lost data value, we use the cost to receive 1MHz from a satellite link as a proxy. Our research has shown that building, launching, and operating a new satellite with 15 transponders for ten years will cost around \$300 million (<http://www.satsig.net/ivsacos.htm>). The cost of leasing a transponder costs approximately \$2million per year. The transponder bandwidth is 36MHz, which means that this 1 MHz lease cost is approximately \$0.0018 per second. To estimate the duration of an interference event, we assume that this would be the average length of an SU session. For a voice call, this would be 2 min, for a data session, this would be the duration of a session. We will go with 2 min as a starting point, so this would be 0.0018*2*60. The SU will use the 15MHZ bandwidth which means that (0.0018*2*60*15) the value of the lost data for each interfering event will cost \$3.24. Although, we will assume that the maximum changeable enforcement cost that can be reached in this study is \$3.24 to make it more feasible for the reader.

harmful interference to PU. Because the SU can repeat the violation act as long as the penalty is fine and not upgraded.

Commented [MW2]: I'm not sure what you're trying to say in this sentence.

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8.3 Ex-post enforcement only- Graduated Response Penalty Approach

But a purely remunerative penalty function nor punitive penalty as an ex-post-only enforcement may not be the best strategy because it might not be large enough to stop the SU from interfering with the PU. A broader framework for evaluating the role of the ex-post-only enforcement would be a better approach to stop the SU from conducting harmful interference to the PU. There are number of aspects to consider, including what the sanctions are and how these should be applied to enforce the PU's rights.

We hypothesize an adjudication system by an enforcer that applies different enforcement sanctions on the Secondary User (SU). The enforcement sanctions would be upgraded gradually in response to the SU's interfering behavior. The graduated response idea is used in the Internet for Internet Service Provider (ISP) to check, conditionally suspend, or disconnect internet access to a subscriber who had received three warning letters of alleged copyright infringement. The idea came from the baseball rule of "three strikes and you are out" and at the start it was known as "three strikes" [17]. The graduated response approach is used in UK, France and other countries.

Response	Power level	Harmful interference time period
1	$-8 \text{ dB} \leq \text{SINR} < 9 \text{ dB}$	Warning
2	$-9 \text{ dB} \leq \text{SINR} < -10 \text{ dB}$	Remunerative penalty
3	$\text{SINR} = -10 \text{ dB}$	Punitive penalty
4	$\text{SINR} > -10 \text{ dB}$	Forfeiture Proceeding guidelines

Table 1: Ways of implementing Graduate Response in Spectrum Sharing

There are many ways to implement the "three strikes" or graduated response idea in spectrum sharing and it depends on the agreement between PU and SU. Table 1 shows two of the graduated response techniques. Here, the agreement could require dividing the power limits into three levels, or the time period of the harmful interference. Or it may combine both ways for more efficiency. The first column in table 1 shows when the agreement requires dividing the power limits into three levels.

- 1- If the SU-mobile device transmitting SINR level reaches -8 dB, the PU will not lose any data because this power level is less than the harmful level. The enforcer will send a warning to the SU. When the SU receives the warning, it would have the chance to:
 - a. Disconnect SU-mobile device,
 - b. Send a message to lower its power,
 - c. Or transfer SU-mobile device to alternative band.
- 2- If SU-mobile device transmitting SINR level reaches -9dB it could still receive the PU's data because this power level is less than the harmful level. The enforcer would start penalizing each SU-mobile device using the remunerative penalty approach. If penalty values exceed the forfeiture maximum limit of \$160,000, the enforcer would go to the second strike. When the SU receives the warning, it would have the chance to:
 - a. Disconnect SU-mobile device,
 - b. Send a message to lower its power,

- c. Or transfer SU-mobile device to alternative band.
- 3- If SU-mobile device transmitting SINR level reaches -10dB, the PU might start losing data because this power level reached the harmful level. The enforcer would upgrade the penalties from remunerative to punitive penalties. When the SU receives the penalties, it would have the chance to:
 - a. Disconnect SU-mobile device,
 - b. Send a message to SU-mobile devices to lower its power,
 - c. Or transfer SU-mobile device to alternative band.
- 4- If SU-mobile device transmitting SINR level is exceeds -10dB or the punitive penalty values exceed the forfeiture maximum limit of \$160,000. The enforcer would go to the third strike to conditionally suspend the SU license.

The enforcer could use the same procedure in the second column of table 1 but the time of conducting the harmful interference is used instead of the power level. For the purpose of this paper, we will follow one type of interference and compare it with the ex-post-only enforcement that is using the remunerative penalty.

The SU may not agree with these steps because they are not covered by the statute. SU may argue with that because the Communications Act of 1934 section 501 ordered the maximum general penalty "if any person willfully and knowingly does or cause suffer to be done any act, matter, or thing omits or fails to do any act, matter, or thing in this Act required to be done, or willfully and known causes or suffers such omission or failure, shall upon conviction thereof, be punished for which no penalty more than \$10,000". In that case, it is the policymaker of CSMAC-enforcement subcommittee to recommend such an update to the Communications Act of 1934. Or, the enforcer could update the procedures to:

- 1- If SU-mobile device transmitting SINR level reaches -8 dB. The PU will not lose any data because this power level is less than the harmful level. The enforcer will send a warning to the SU. When the SU receive the warning, it will have the chance to:
 - a. Disconnect SU-mobile device,
 - b. Send a message to lower its power,
 - c. Or transfer SU-mobile device to alternative band.
- 2- If the SU-mobile device transmitting SINR level reaches -9dB, the PU's data could still be received because this power level is less than the harmful level. The enforcer will start penalizing each SU-mobile device using remunerative penalty approach.
- 3- If the SINR reaches -10dB or the remunerative penalty values exceeds the forfeiture maximum limit of \$10,000, the enforcer will go to the second strike of using punitive penalty approach. When the SU receive these penalties, it will have the chance to:
 - a. Disconnect SU-mobile device,
 - b. Send a message to lower its power,
 - c. Or transfer SU-mobile device to alternative band.
- 4- If it is
 - a. The first time for the SU to exceeds -10 dB, and if the penalty values exceeds the maximum forfeiture penalty value of \$160,000 or if SU does not stop transmitting, the enforcer would have the authority to conditionally suspend the SU license.
 - b. Repeated actions by the SU, and if the penalty value exceeds the maximum forfeiture penalty value of \$1,575,000 or if SU does not stop transmitting, the enforcer would have the authority to conditionally suspend the SU license.

In addition, the graduated response approach would cost more than the remunerative approach because it requires a more advanced adjudication system. The advanced adjudication system would, however, have an ex-post components that could efficiently and effectively adjudicate claims of interference.

Commented [MW3]: I would consider deleting this, since we're not doing a legal analysis. You could replace it with a caveat that this approach may require policy changes.

9. Conclusion

Determining the role of ex-post enforcement in a cooperative spectrum sharing scheme is of significant importance since spectrum sharing will without doubt result in interference events. This paper evaluated the role of the ex-post enforcement approach. It did so by using a hypothetical scenario of the recommended protection zones and the entities involved analyze the current enforcement timing measures and evaluate the usage of ex-post-only enforcement measures. The issue with the recommended ex-post enforcement measures by the CSMAC-enforcement subcommittee is that they are suitable for static spectrum allocation policy but are not applicable for cooperative spectrum sharing. In fact they might reduce the incentives for the SU to share the spectrum. Two main points of view were given, which were regulatory and technical points.

The CSMAC-enforcement subcommittee recommended that PU and SU enter into a specific MOU or individual agreement to cover all specific interference enforcement issues. This recommendation would not be an ideal recommendation because it would be under the umbrella of the Communications Act of 1934 and the Forfeiture Proceedings guidelines. In addition, the Forfeiture Proceeding guidelines did not consider the time period of conducting the harmful interference. The time period of the harmful interference is needed when imposing the penalty to cover the expenses of lost data.

Three alternative scenarios were given using ex-post-only enforcement to show the regulator how an ex-post-only enforcement scheme might work. The first scenario, an adjudication system penalizes the SU when the interference level reaches a certain limit received at the PU's antenna with a fine that is equal to the value of the lost data which is remunerative penalty approach. The remunerative penalty approach was used which means a fine imposed to SU that was proportional to the lost value of the lost data by the PU plus the enforcement costs caused by it. The remunerative penalty was imposed for each SU-mobile device conducting harmful interference to the PU's received signal. The penalty also took into account the length of time of the interference. The benefits of using ex-post-only with remunerative approach suggested in [6] for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas, (3) the cost of building the sensors to around the PU's base station to detect harmful interference is less than the one for protection zones because it would have less ranges. The disadvantages of using ex-post-only approach were explained and alternative ex-post-only scenario was explained to overcome these disadvantages.

In the second ex-post-only enforcement scenario, an adjudication system penalizes each SU, when the interference level reaches a certain limit received at the PU's antenna, with much higher amount than the value of the lost data which is called punitive penalty approach. This approach was given to overcome the disadvantages of the remunerative penalty approach. A comparison between the remunerative and different punitive penalty functions was given and it showed how punitive penalty is superior to the previous approach.

Finally, the idea of a broader framework for evaluating the role of the ex-post-only enforcement to stop the SU from conducting harmful interference was put forth. This example hypothesized an adjudication system by an enforcer that applied different enforcement sanctions on the Secondary User (SU). The enforcement sanctions would be upgraded gradually in responding to the SU's interfering behavior. The

ways of implementing the graduated response idea in cooperative spectrum sharing were explained depending on the agreement between PU and SU. The interference levels were divided into three different interference event levels received at the PU's antenna. In the first interference level, the penalty would be proportional to the value of lost data by the PU plus the expected increase in enforcement costs occasioned by it. In the second interference level, when the SU did not optimize the transmission and decided to continue transmitting closer to the PU's antenna, more punitive penalties could be applied. If the SU then optimized transmissions, the net value of a sequence of transmissions would be positive. In the third interference level, when the interference exceeds the threshold that had been suggested in [1, 10] other ex-post enforcement sanctions were suggested. The concerns of these approach were explained and strategies to overcome these concerns were suggested. It was also recommended that either the policymaker of the CSMAC-enforcement subcommittee propose an update to the Communications Act of 1934 or adjust the procedures of adjudication to overcome these concerns.

A comprehensive enforcement framework would include protecting the rights of the SU as well, in addition to having an ex-post component that can efficiently and effectively adjudicate claims of interference.

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Appendix A

Signal Interference-To-Noise Ratio (SINR)

The equation for the SINR can be expressed as:

$$SINR_i = \frac{P_{rPU} G_{ii}}{\sum_{j \neq i} P_{rSU} G_{ij} + n_i}$$

The signal to interference and noise ratio varies with the transmission parameters for SU. It depends on the distance between the PU and the SU, the received power of the PU and SU, the transmitter density, the antenna parameters of the SU and PU, and n_i is the noise. The received power is:

$$P_r = P_t(dB) + G_R(dB) + G_T(dB) - Path\ loss(dB)$$

Where P_r is the received power, P_t is the transmitted power, G_R is the maximum receive antenna gain, G_t is the maximum transmit antenna gain.

To get the received power the path loss must be found first. And to get the path loss, two equations will be used:

- 1- Free Space Path Loss: $FSPL = \frac{4\pi f_c d}{c}$, where f_c is the center frequency, c is the speed of light, and d is the distance. Free Space Path Loss equation used to get the desired received power by the earth station.
- 2- To get the path loss the COST-231 model will be used. This is a propagation model funded by the European COST-231 program. The COST-231 propagation model can be applied to the frequency range (1500- 2000 MHz)¹¹:

$$PL = 46.3 + (33.9 \times \log_{10}(f_c)) - (13.82 \times \log_{10}(ht)) - a(h_{re}) + [44.9 - 6.55 \times \log_{10}(ht)] \times \log_{10} d(i) + C$$

Where PL is the path loss, f_c is the center frequency, $a(h_{re})$ is the mobile antenna correction factors for the effective antenna height in dB:

$$a(h_{re}) = \begin{cases} 8.29(\log_{10}(1.54h_{re}))^2 - 1.1 & \text{if } f_c \leq 300 \text{ MHz} \\ 3.2(\log_{10}(11.75h_{re}))^2 - 4.98 & \text{if } f_c > 300 \text{ MHz} \end{cases}$$

h_{te} is the effective transmitter antenna height ranging from 30 to 200 meter, h_{re} is the effective receiver antenna height ranging from 1 to 10 meters, d is the distance between the transmitter and the receiver in kilometers, and the value of $C = 0dB$ for medium-size city and $C = 3dB$ for metropolitan areas.

- 3- Then to calculate the noise the following equation can be used:

$$n_{dB} = K + T_o + F + 10 \times \log_{10}(BW)$$

Where K is 198.6, $T_o = 24.6dB$, F is the noise figure, and BW is the bandwidth.

Our Assumption for Building the Model

We assumed: 1) the center frequency at 1702.5 MHz. 2) EIRP value includes the effects of antenna gain, antenna efficiencies, transmitter power, coupling and wave guide losses. And when the EIRP is known, no additional information about the transmitter is required. The EIRP used in the model is 8.1dBW¹². 3) the

¹¹ "A guide to the wireless engineering body of knowledge (WEBOK), 2d ed." Reference & Research Book News Dec. 2012. Academic OneFile. Web. 8 Jan. 2015. Available: http://go.galegroup.com/ps/i.do?id=GALE%7CA312255990&v=2.1&u=upitt_main&it=r&p=AONE&sw=w&asid=12466ede5e760fb56d766a82ef4da1e7

¹² This value based on the ITU-P recommendation S.A. 1026

distance between the satellite and the earth station used 35785 km (approximately 22,236 mile). 4) Free Space Path Loss equation used to get the desired received power by the earth station.

For the uplink of LTE mobile network (SU) we assumed: 1) the center frequency at 1702.5 MHz. 2) COST-231 used to calculate the path loss to get the interfered received power. 3) $C=3$ in the COST-231 because we are going to use it in the metropolitan area. 4) Received antenna height (h_t) used 30 meters. 5) Transmitter height used 1.5 meter. 7) Transmitted power used 23dBm which is the highest transmission power for the LTE mobile phones. 7) 100,000 uniformly distributed mobile phones (SU) at a time.

The noise value used is 0 Watt because we assume the antenna receiver is engineered to deal with and reject normal noise.